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ENERGETIC AND EXERGETIC ANALYSIS OF CRYOGENIC SYSTEMS USED IN A DETRITIATION PILOT PLANT

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In societatea modernă se constata că scopul final al oricărei întreprinderi economice de producție sau servicii este de a obține profit deci produsele realizate sau serviciile prestate sunt doar etape intermediare ale procesului de obținere a profitului. Scopul lucrării este de a exemplifica un model de analiza cu aplicatie în instalații criogenice capabil să extindă problemele tehnice prin analize exergoeconomice în sensul dezvoltarii științifice. Am propus ecuații pentru a calcula entalpia hidrogenului şi heliului. În lucrare sunt studiate două configurații de cicluri criogenice pentru determinarea soluției investiționale optime pentru ciclurile de răcire aferente coloanei de distilare a Instalației Pilot Criogenic pentru Separarea Tritiului şi Deuteriului.

In modern society is found that the ultimate goal of any economic production or services is to obtain profits, so the products or services are only intermediate steps in the process of obtaining a profit. This work exemplifies a model of energetic-exergetic analysis with applications in cryogenic equipment able to extend the technical analysis in exergoeconomic terms for scientific development. We proposed equations to calculate the enthalpy of hydrogen and helium. In two configurations of cryogenic cycles are studied in order to determine the optimal solution of the associated cryogenic cooling for distillation column of the Pilot Plant for Tritium and Deuterium separation.

Keywords: thermoeconomic analyses, optimal solution, cryogenic cycles

1. Introduction

The experimental Pilot plant for tritium and deuterium separation, part of National Research and Development Institute for Cryogenics and Isotopic Technologies - ICSI Rm.Valcea, has as principal target to establish the technology of the water-hydrogen catalyzed isotopic exchange[9] and cryogenic distillation for mixtures of hydrogen and its isotopes diatomic species[7].

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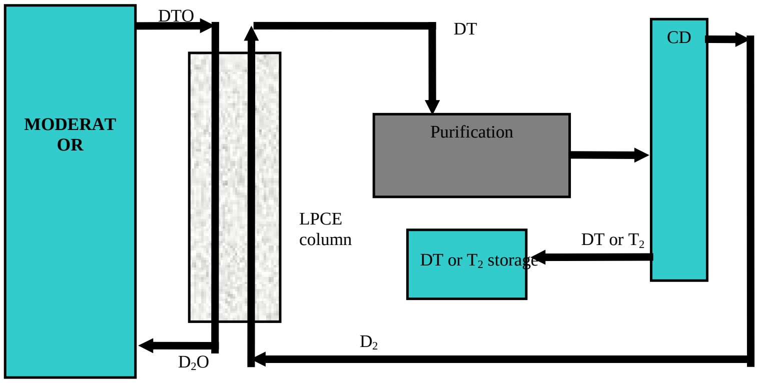


Fig. 1

The most important part of the experimental Pilot plant for tritium and deuterium separation is module 300(cryogenic distillation of hydrogen/deuterium/tritium mixture). The principal goals of that module are:

a) to insure and maintain the proper temperature for hydrogen condensation in the head of the distillation column,
b) to elaborate the high efficiency contact elements on hydrogen isotopes separation.

Therefore, to accomplish the task presented at point a), the hydrogen distillation condenser column is cooled within a cryogenic cycle which is ensuring a level of temperature within 20-30 K, corresponding to the working pressure of the distillation column.

The objective of the paper is to analyze the solutions to achieve the refrigeration power[8] of the distillation column condenser.

There are two types of cryogenic cycles:

1. helium cycle
2. hydrogen cycle

2. Calculation of helium cycle

2.1 Operation description: Helium gas is compressed in compressor CP up to 15 bar pressure, then it is cooled in heat exchanger HE1, then it is cooled in liquid nitrogen bath S and continues to be cooled in the heat exchanger HE2, then one part (1-M) enters the turbo-expander and another part (M) continues to be cooled in heat exchangers HE3 and HE4, then enters the throttle valve and obtains liquid fraction(y) in a separator vessel. The cycle is calculated for 1kg of compressed gas.

2.2 Operating conditions:

$p_1 = 1\ bar$
$p_2 = 15\ bar$
- Isentropic efficiency of compressor $\eta_c = 0.6$
- Turbine efficiency $\eta_d = 0.7$
- Heat intake through insulation $q_i = 2\ \frac{KJ}{Kg}$
- Temperature of liquid nitrogen at vapor pressure p = 1 bar is: $T_{vN2} = 77.34\ K$
- Helium temperature at the exit from the bath of nitrogen: $T_4 = 80K$
- Helium temperature before entering in the last heat exchanger: $T_6 = 11K$

At the three cooling steps, we imposed the following temperature differences required for heat transfer and indicate the incomplete heat recovery in heat exchangers:

$\Delta t_{c1} = 5K$, $\Delta t_{c2} = 3K$, $\Delta t_{c3} = 1K$

Table 1

Temperature K	$T_1 = 293K$	$T_{13} = 288K$	$T_{12} = 77K$	$T_{10} = 10K$

Losses of cold to the environment due to imperfect isolation are considered equally distributed on each of the four heat exchangers.

The enthalpy is determined by the equations of two variables knowing the temperature and pressure:

$$h_{He} = -1542{,}734333902 + 4{,}408574501 \cdot T_1 + 0{,}024170375 \cdot T_1^2 - \\ -0{,}000118626 \cdot T_1^3 - \frac{4{,}301221463 \cdot p_1}{\left(\frac{T_1}{100}\right)^{-2{,}426044442}} \left[\frac{KJ}{Kg}\right] \quad (2.1)$$

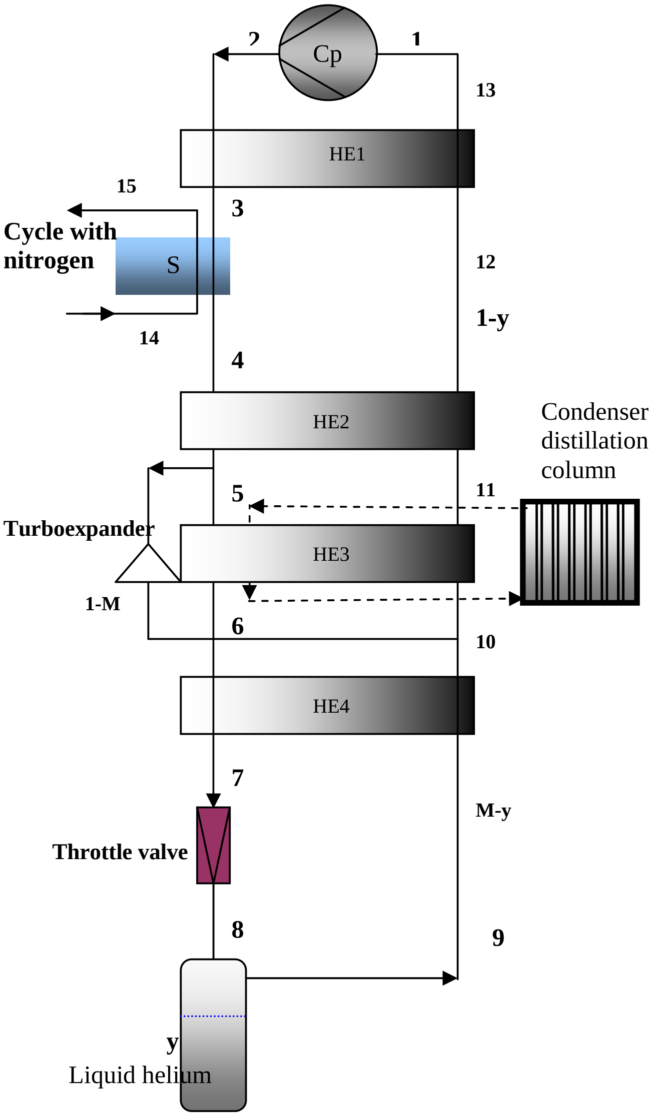


Fig. 1 The helium cycle

Table 2

Enthalpy $\frac{KJ}{Kg}$	$h_4 = 428.2$ $h_{13} = 1506$	$h_6 = 53.58$ $h_2 = 1535$
Enthalpy $\frac{KJ}{Kg}$	$h_L = 6.34$ $h_{10} = 65.72$	$h_9 = 30.97$ $h_1 = 1532$

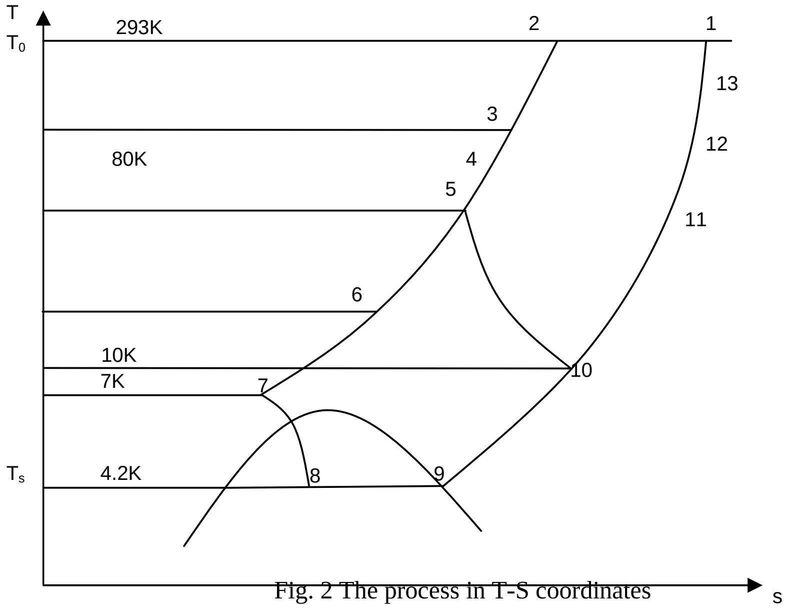
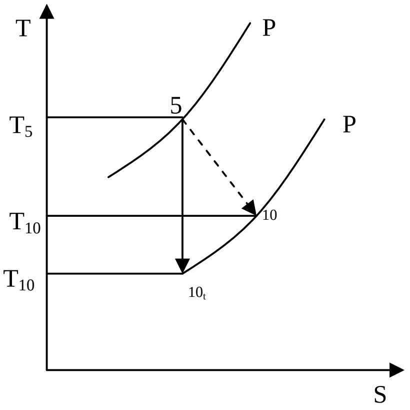


Fig. 2 The process in T-S coordinates

The enthalpy h5 is determined by the expression of internal efficiency (adiabatic) of the turbine:

$$\eta_d = \frac{h_5 - h_{10}}{h_5 - h_{10t}} \tag{2.2}$$



detention

Fig.3

Known: $\eta_d = 0.7$

$h_{10} = 65.72 \ \frac{KJ}{Kg}$ is obtained: $h_5 = 135.2 \ \frac{KJ}{Kg}$

One can write six independent equations of heat balances with six variables, so the system is fully determined.

$M \cdot h_8 + q_i = y \cdot h_L + (M - y) \cdot h_9$ For separated vessel (2.3)

$M \cdot (h_6 - h_7) + q_i = (M - y) \cdot (h_{10} - h_9)$ for HE4 (2.4)

$M \cdot (h_5 - h_6) + q_i = (1 - y) \cdot (h_{11} - h_{10})$ for HE3 (2.5)

$1 \cdot (h_4 - h_5) + q_i = (1 - y) \cdot (h_{12} - h_{11})$ for HE2 (2.6)

$1 \cdot (h_2 - h_3) + q_i = (1 - y) \cdot (h_{13} - h_{12})$ for HE1 (2.7)

$1 \cdot (h_3 - h_4) = m_{N2} \cdot (h_{15} - h_{14})$ for bath of nitrogen S (2.8)

We obtain

$y = 0.057 \ \frac{\text{kg liquid}}{\text{kg compressed gas}}$; $M = 0.407 \ \frac{\text{kg liquid}}{\text{kg compressed gas}}$;

$m_{N2} = 0.404 \ \frac{\text{kg liquid}}{\text{kg compressed gas}}$

Table 3

Enthalpy $\frac{KJ}{Kg}$	$h_7 = 28.616$	$h_8 = 28.616$
Enthalpy $\frac{KJ}{Kg}$	$h_{11} = 103.035$	$h_3 = 508.977$

Real cooling power, corresponding to the value of y:

$$q_{or} = y \cdot (h_1 - h_L) \tag{2.9}$$

$q_{or} = 86.963 \ \frac{KJ}{Kg}$

Specific work consumed by the compressor:

$R = 2.0785 \ \frac{KJ}{Kg \cdot K}$

$$l_c = \frac{1}{\eta_c} \cdot R \cdot T_1 \cdot \ln\left(\frac{p_2}{p_1}\right) \tag{2.10}$$

$$l_c = 2749\ \frac{KJ}{Kg}$$

Specific work of turboexpander:

$$l_d = \eta_d \cdot (1 - M) \cdot (h_5 - h_{10}) \tag{2.11}$$

$$l_d = 30.901\ \frac{KJ}{Kg}$$

Total specific work, used in the cycle:

$$l = l_c - l_d \tag{2.12}$$

$$l = 2718\ \frac{\text{KJ}}{\text{kg compressed gas}}$$

The specific energy consumption for producing 1 kg of liquid helium:

For the auxiliary nitrogen cycle the specific energy consumption for producing liquid nitrogen will be considered,

$$l_{uN_2} = 1.6\ \frac{\text{KWh}}{\text{kg compressed N}_2}$$

$$l_{N_2} = l_{nN_2} \cdot m_{N_2} \tag{2.13}$$

$$l_{N_2} = 0.646\ \frac{\text{KWh}}{\text{kg compressed N}_2}$$

$$l_{efN_2} = 2327\ \frac{\text{KJ}}{\text{kg compressed N}_2} \tag{2.14}$$

The specific energy consumption for producing 1 kg of liquid He:

$$l_L = \frac{1 + l_{efN_2}}{y} \tag{2.15}$$

$$l_L = 88510\ \frac{\text{KJ}}{\text{kg liquid}}$$

$$L_L = \frac{l_L}{3600} \tag{2.16}$$

$$L_L = 24.585 \frac{\text{KWh}}{\text{kg liquid He}}$$

The power used for refrigeration of hydrogen condenser at 25 K, corresponding to value of M:

We consider the flow of helium

$$m_{He} = 0.047 \frac{Kg}{h}$$

$$P_{25} = M \cdot (h_5 - h_6) \cdot m_{He} \tag{2.17}$$

$$P_{25} = 1561\ KW$$

2.3 Exergetic analysis of helium cycle

$$\Delta h_{T_0} = h_2 - h_1 \tag{2.18}$$

$$\Delta h_{T_0} = 3 \frac{KJ}{Kg}$$

$$q_f = h_1 - h_L \tag{2.19}$$

Heat can be taken in the isobar vaporization process of the liquified gas fraction:

$$Q_f = y \cdot q_f \tag{2.20}$$

$$Q_f = 86.963 \frac{KJ}{Kg}$$

Specific isothermal work of compression:
Index L represented the liquid state,

$$s_L = 1.18 \frac{KJ}{Kg \cdot K}$$

$$s_1 = 29.805 \frac{KJ}{Kg \cdot K}$$

$$s_2 = 24.173 \frac{KJ}{Kg \cdot K}$$

$$l_{T_1} = T_1 \cdot (s_2 - s_1) \tag{2.21}$$

$$l_{T_1} = 1650 \frac{KJ}{Kg}$$

Efficiency of cryogenic cycle:

$$e_f := \frac{Q_f}{l_{T1}} \tag{2.22}$$

$e_f = 0.053$

Average thermodynamic temperature of the isobar vaporization process:

$$T_{mf} = \frac{h_1 - h_L}{s_1 - s_L} \tag{2.23}$$

$T_{mf} = 53.298\ K$

Efficiency of reversed refrigeration Carnot cycle:

$$e_c = \frac{T_{mf}}{T_1 - T_{mf}} \tag{2.24}$$

$e_c = 0.222$

The degree of reversibility of the cycle:

$$r = \frac{e_f}{e_c} \tag{2.25}$$

$r = 0.237$

Loss caused by throttling irreversibility:

$$s_8 = 7.29\ \frac{KJ}{Kg \cdot K}$$

$$s_7 = 8.24\ \frac{KJ}{Kg \cdot K}$$

$$P_{ir1} = T_1 \cdot (s_7 - s_8) \tag{2.27}$$

$$P_{ir1} = 278.35\ \frac{KJ}{Kg}$$

3. Calculation of hydrogen cycle

3.1 Operation description: Hydrogen gas is compressed in the ompressor CP up to 80 bar pressure, then it is cooled in the heat exchanger HE1, then is cooled in liquid nitrogen bath S, continues to be cooled in the heat exchanger HE2 then enters the throttle valve and obtain liquid fraction (y) in separator vessel. The cycle is calculated for 1kg of compressed gas.

3.2 Operating conditions:

$p_1 = 1\ bar$

$p_2 = 80\ bar$

- Isentropic efficiency of compressor: $\eta_c = 0.6$
- Turbine efficiency: $\eta_d = 0.75$
- Heat intake through insulation: $q_i = 2\ \frac{KJ}{Kg}$

- Temperature of liquid nitrogen at vapor pressure p = 1 bar is: $T_{vN2} = 77.34\ K$
- Hydrogen temperature at the exit from the bath of nitrogen: $T_4 = 80\ K$

At the two cooling steps, we imposed the following temperature differences required for heat transfer and indicate incomplete heat recovery in heat exchangers:

$\Delta t_{c1} = 5\ K$

$\Delta t_{c2} = 3\ K$

Losses of cold by environment due to imperfect isolation are considered equally distributed on each of the two heat exchangers.

Table 4

Temperature K	$T_1 = 293$	$T_8 = 77$	$T_9 = 288$

Enthalpy in the main points of the cycle:

Enthalpy is determined by the equations of two variables knowing the temperature and pressure:

$$h_{H_2} = 993{,}329948555 + 18{,}183906386 \cdot t + 0{,}032519359 \cdot t^2 - 0{,}000028680 \cdot t^3 - \frac{-85{,}381510427 \cdot p}{\left(\frac{t}{100}\right)^{13{,}607810291}} \tag{3.1}$$

Table 5

Enthalpy $\frac{KJ}{Kg}$	$h_1 = 4127$ $h_4 = 1220$	$h_2 = 4150$ $h_L = 740$
Enthalpy $\frac{KJ}{Kg}$	$h_7 = 750$ $h_8 = 1390$	$h_9 = 4120$

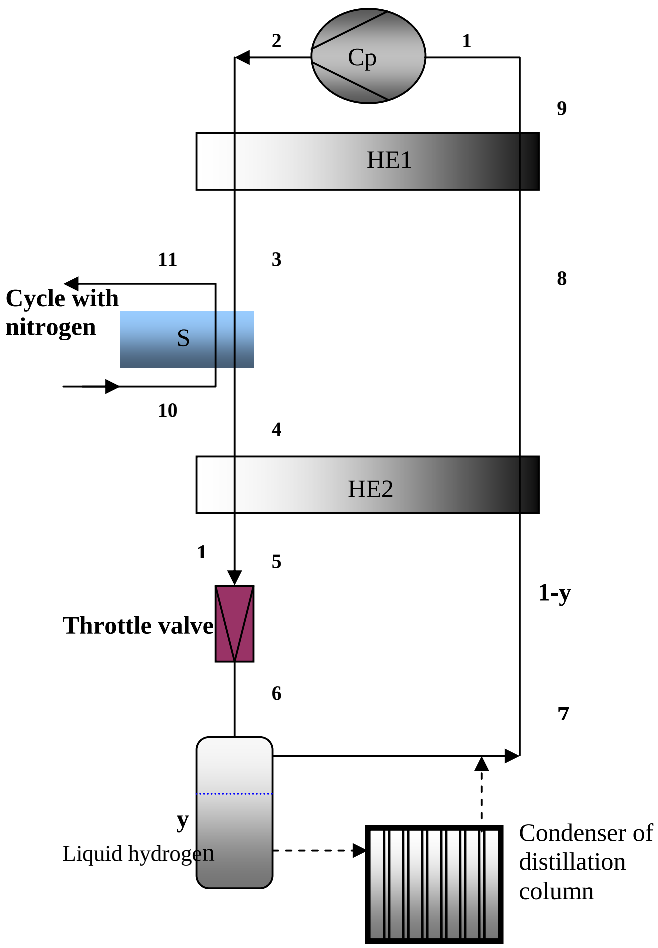


Fig. 4 The hydrogen cycle

One can write four independent equations of the heat balance with four variables, so the system is fully determined.

$$1 \cdot h_6 + q_i = y \cdot h_L + (1-y) \cdot h_7 \qquad \text{For separated vassel} \tag{3.2}$$

$$1 \cdot (h_4 - h_5) + q_i = (1-y) \cdot (h_8 - h_7) \quad \text{for HE2} \tag{3.3}$$

$$1 \cdot (h_2 - h_3) + q_i = (1-y) \cdot (h_9 - h_8) \quad \text{for HE1} \tag{3.4}$$

$$1 \cdot (h_3 - h_4) = m_{N_2} \cdot (h_{11} - h_{10}) \qquad \text{for bath of nitrogen S} \tag{3.5}$$

We obtain

$$y = 0.3 \ \frac{\text{kg liquid}}{\text{kg compressed gas}}$$

$$h_5 = 774\ \frac{KJ}{Kg},\quad m_{N_2} = 5.105\ \frac{Kg}{h},\quad h_3 = 2241\ \frac{KJ}{Kg}$$

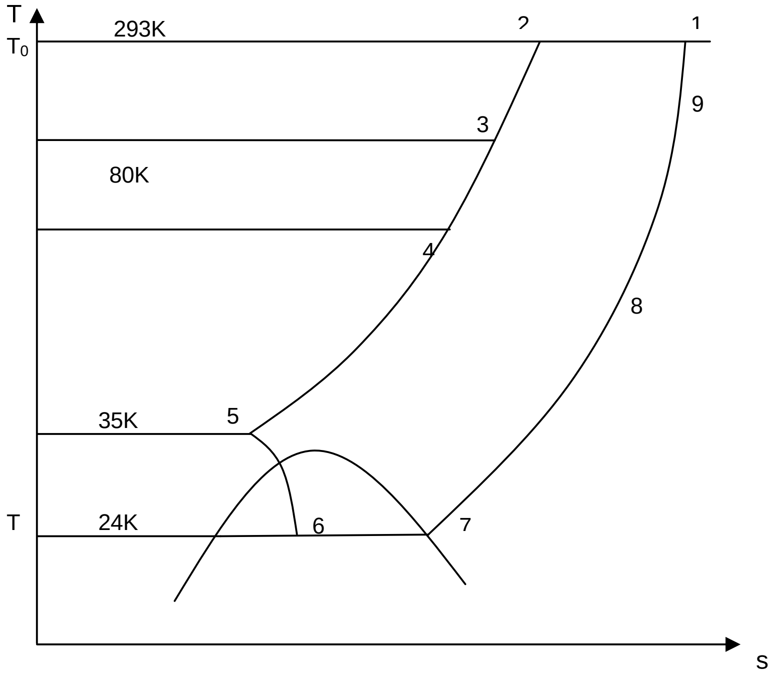


Fig. 5 The process in T-S coordinates

Real specify cooling power, corresponding to the value of y:

$$q_r = y \cdot (h_1 - h_L) \tag{3.6}$$

$$q_r = 1016\ \frac{KJ}{Kg}$$

The power used for refrigeration of hydrogen condenser at 25 K temperature, corresponding to value of M:

We consider the flow of hydrogen

$$m_{H_2} = 0.5\ \frac{Kg}{h}$$

$$P_{25} = (h_1 - h_L) \cdot y \cdot m_{H_2} \tag{3.7}$$

$$P_{25} = 1.5\ \frac{\text{KWh}}{\text{kg liquid H}_2}$$

Specific work consumed by the compressor:

$$R = 4.1217 \frac{KJ}{Kg \cdot K}$$

$$l_c = \frac{1}{\eta_c} \cdot R \cdot T_1 \cdot \ln\left(\frac{p_2}{p_1}\right) \tag{3.8}$$

$$l_c = 8820 \frac{KJ}{Kg}$$

Total specific work, used for the cycle:

$$l = l_c \tag{3.9}$$

$$l = 8820 \frac{\text{KJ}}{\text{kg compressed gas}}$$

The specific energy consumption for producing 1 kg of liquid hydrogen:
For the auxiliary nitrogen cycle the specific energy consumption for producing liquid nitrogen will be considered,

$$l_{uN_2} = 1.6 \frac{\text{KWh}}{\text{kg compressed N}_2}$$

$$l_{N_2} = l_{uN_2} \cdot m_{N_2} \tag{3.10}$$

$$l_{N_2} = 8.168 \frac{\text{KWh}}{\text{kg compressed N2}}$$

$$l_{efN_2} = 29400 \frac{\text{KJ}}{\text{kg compressed N}_2} \tag{3.11}$$

The specific energy consumption for producing 1 kg of liquid He:

$$l_L = \frac{1 + l_{efN_2}}{y} \tag{3.12}$$

$$l_L = 12740 \frac{\text{KJ}}{\text{kg liquid}}$$

$$L_L = \frac{l_L}{3600} \tag{3.13}$$

$$L_L = 35.393 \frac{\text{KWh}}{\text{kg liquid He}}$$

3.3 Exergetic analysis of hydrogen cycle

$\Delta h_{T_0} = h_2 - h_1$; $\Delta h_{T_0} = 23 \frac{\mathrm{KJ}}{\mathrm{kg}}$; $q_f = h_1 - h_L$

Heat can be taken in the isobar vaporization process of the liquefied gas fraction:

$$Q_f = y \cdot q_f \tag{3.14}$$

$$Q_f = 1016 \frac{KJ}{Kg}$$

Specific isothermal work of compression:
Index L represented the liquid state,

$s_L = 32 \frac{KJ}{Kg \cdot K}$ $s_1 = 63 \frac{KJ}{Kg \cdot K}$; $s_2 = 46 \frac{KJ}{Kg \cdot K}$

$$l_{T_1} = T_1 \cdot (s_2 - s_1) \tag{3.15}$$

$$l_{T_1} = 4981 \frac{KJ}{Kg}$$

Efficiency of cryogenic cycle:

$$e_f = \frac{Q_f}{l_{T_1}} \tag{3.16}$$

$e_f = 0.204$

Average thermodynamics temperature of the isobar vaporization process:

$$T_{mf} = \frac{h_1 - h_L}{s_1 - s_L} \tag{3.17}$$

$$T_{mf} = 109.258\ K$$

Efficiency of reversed refrigeration Carnot cycle:

$$e_c = \frac{T_{mf}}{T_1 - T_{mf}} \tag{3.18}$$

$e_c = 0.595$

The degree of reversibility of the cycle:

$$r = \frac{e_f}{e_c} \tag{3.19}$$

$r = 0.343$

Loss caused by throttling irreversibility:

$s_6 = 32 \frac{KJ}{Kg \cdot K}$, $s_5 = 14 \frac{KJ}{Kg \cdot K}$

$$P_{ir1} = T_1 \cdot (s_6 - s_5) \tag{3.20}$$

$$P_{ir1} = 5274 \frac{KJ}{Kg}$$

Table 6

Comparison of the cycles

Working gas	Isothermal compression mechanical work input $\frac{KJ}{Kg}$	Cryogenic efficiency of the cycle:	The degree of reversibility of the cycle:	Loss caused of the throttling irreversibility: $\frac{KJ}{Kg}$
Hydrogen	$l_{T_1} = 4981$	$e_f = 0.204$	$r = 0.343$	$P_{ir1} = 5274$
Helium	$l_{T_1} = 1650$	$e_f = 0.053$	$r = 0.237$	$P_{ir1} = 278.3$

4. Conclusions

Optimal partitioning or optimal allocation of constrained quantities is a by-product of the optimization of flow geometry. It is encountered every time global performance is maximized: optimal allocation is another way of interpreting the special optimization of the flow arrangement, i.e., the optimal spreading of imperfection (irreversibility)[1],[6].

Thermodynamic analysis of the two cycles reveals that the hydrogen cycle obtains a higher degree of reversibility, as well as a higher cryogenic efficiency[2].

From an economic point of view the cycle with hydrogen presents a lower economic cost of achieving in comparison with the helium cycle, because the cycle with helium contains the high cost of the turboexpander. From the technological and of the maintenance point of view, the hydrogen cycle has an advantage because this cycle has lower maintenance costs and operating costs in comparison with the helium cycle. Hydrogen also requires, lower production costs compared with helium [3]. If we compare the two working gases (hydrogen and helium) we see that hydrogen has superior specific heat compared with helium, and this constitutes an advantage in the functionality and stability of that cycle.

The Carnot efficiency of cryogenic cycle with hydrogen is higher than the Carnot efficiency of helium cycle, this it explicable by the fact that the minimum temperature of liquid helium is less than the one of hydrogen.

Cryogenic cycle function is to cool the condenser for the distillation column (fig. 1), and in case of hydrogen cooling, the condenser is a more compact construction because hydrogen cycle offers a better exchange coefficient and a smaller surface exchange [4],[5].

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